

Air Quality and Economic Trade-Offs of Relaxing California's Gasoline Volatility Limits

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Abstract

Long-standing emission control policies may become less cost-effective and warrant reassessment as technologies and knowledge of atmospheric chemistry evolve. This issue is particularly important for California, which faces persistent summertime ozone nonattainment and the highest gasoline prices in the United States. Since the 1990s, California has adopted stringent summer gasoline volatility limits to control ozone, which increase gasoline production costs and prices, yet their air quality impacts under present-day conditions remain unclear. Emissions modeling indicates that replacing summer-blend gasoline with higher-volatility winter-blend gasoline would increase statewide anthropogenic reactive organic gas emissions by 2.7% in July and 1.1% in October. High-resolution air quality simulations show population-weighted maximum daily eight-hour average ozone increases of 0.075 ppb (0.14%) and 0.006 ppb (0.01%) in July and October, respectively, while the changes in PM_{2.5} are negligible. Winter-blend gasoline organic gas emissions are less reactive, partially offsetting and even overturning air quality penalties predicted from volatility alone. Estimated monthly production-cost savings of US\$70–73 million, with potentially larger consumer savings, exceed monetized health effects. These findings demonstrate the value of integrated air quality, health, and economic assessment in informing environmental regulations.

Introduction

California continues to face two challenges that are often considered separately: persistent summertime ozone nonattainment and recurring gasoline price surges. Ozone formation is driven by photochemical reactions involving reactive organic gases (ROG) and nitrogen oxides (NO_x)

and is enhanced by high temperature and strong solar radiation^{1,2}. At the same time, California experiences the highest gasoline prices in the United States, owing in part to its isolated fuel market and stringent fuel specifications designed to reduce ROG emissions³⁻⁷. These dual challenges have motivated interest in research and policy efforts to improve fuel market flexibility while maintaining air quality protection.

Seasonal gasoline volatility standards in California represent a policy trade-off between economic costs and air quality. Gasoline evaporation is a source of anthropogenic ROG emissions⁸, and evaporative emissions increase during warm weather. To reduce summertime ozone formation by controlling ROG emissions, federal and state fuel programs limit the volatility of gasoline sold during designated summer control periods. Gasoline that meets the lower-volatility requirements is commonly referred to as summer-blend gasoline, whereas gasoline sold outside the control period is referred to as winter-blend gasoline. Gasoline volatility is commonly measured by Reid vapor pressure (RVP)⁹; summer-blend gasoline requires additional refining to achieve a low RVP by removing high volatility components. California's reformulated gasoline (CaRFG) program imposes a stricter set of fuel properties and components than the federal program^{10,11} and sets the lowest RVP requirement for summer-blend gasoline, at approximately 7.0 psi, compared with the federal limit of 7.4-9.0 psi^{9,12}. The RVP limits are lifted after the control period ends, while the CaRFG fuel properties and specifications requirements remain for winter-blend gasoline¹³.

These standards have historically delivered substantial emission reductions. According to the California Air Resources Board (CARB), the impact of the CaRFG program was equivalent to the removal of 3.5 million on-road vehicles in 2003¹⁴. However, the improvement of vehicle technologies and evaporative emission controls as well as fleet turnover have reduced emissions from on-road sector over the past decades¹⁵⁻¹⁸ (Fig. S1). In addition, the benefits of volatility controls are also dependent on regional and seasonal conditions because ozone formation is strongly influenced by meteorological and atmospheric photochemical conditions^{1,19-21}. As anthropogenic emissions have declined and temperatures have continued to rise under climate change, ozone sensitivity and atmospheric conditions have evolved²²⁻²⁵. These changes raise a policy-relevant question: to what extent do stringent seasonal gasoline volatility standards provide air quality benefits under present-day conditions in California? The question has become increasingly relevant as California evaluates options to mitigate gasoline price spikes and improve fuel supply resilience^{6,26}. These pressures are intensifying as the state is losing roughly 17% of its in-state refining capacity over 2025-2026 with the closure of two major refineries²⁷; it is very challenging to replace this capacity because the special fuel specifications compared to national standards and the lack of inbound pipeline. In 2022 and 2023, CARB authorized temporary earlier transitions to winter-blend gasoline to help relieve the emergency of gasoline price spikes by increasing fuel supply flexibility^{13,28}, as winter-blend gasoline has higher volatility and is generally easier and less expensive to produce²⁹. However, the air quality consequences of using higher-volatility gasoline earlier in the control season have not been comprehensively quantified under present-day emissions.

Previous studies, conducted largely during the early implementation of CaRFG in the 1990s and early 2000s, evaluated its air quality benefits using emission testing, monitoring observations, and historical policy analyses. Larsen et al. (2001)³⁰ analyzed the ozone benefits before and after the adoption of CaRFG, and found that 8-13% of ozone concentration reductions are attributed to CaRFG in the Los Angeles area. Analysis of ozone observational data from 1996-2003 estimated that California's fuel regulations reduced ozone concentrations by approximately 9.1%³¹. Consistent with these findings, vehicle tunnel testing and ROG measurements made during 1994-1997 demonstrated that CaRFG could reduce on-road evaporative emissions due to the reductions in gasoline vapor pressure^{32,33}. However, whether gasoline volatility standards continue to deliver comparable air quality benefits under present-day conditions remains unknown. No study has evaluated the effects of relaxing seasonal volatility standards using regional chemical transport modeling, or linked those effects to population exposure and health outcomes.

Here we address the aforementioned knowledge gaps and advance our understanding of present-day air quality, health and economic trade-offs of relaxing California's seasonal gasoline volatility standards. We develop scenarios introducing higher-volatility winter-blend gasoline in July and October, representing peak-summer and late-season ozone conditions, and distinguish the effects of increased evaporative emissions from those of changing fuel composition. We integrate statewide emissions inventories, high-resolution chemical transport modelling, population-weighted exposure and health impact assessment with estimates of fuel production costs. This framework reveals how timing and fuel properties shape the environmental and economic consequences of gasoline volatility controls, providing broader insights into the reassessment of long-standing emission control policies as technologies, atmospheric conditions, and markets evolve.

Results

California experiences large seasonal changes in fuel volatility

California's summer gasoline volatility limits are more stringent than the federal summer standard and vary across RVP control areas (Fig. 1), based on CARB's surveyed RVP values for gasoline stations statewide³⁴. The summer-blend gasoline control period varies by region and is determined by historical and current ozone levels and regional meteorology²⁹. Area A, which includes the South Coast and other Southern California air basins, has the longest control period, from April through October, reflecting the persistent summer ozone nonattainment of National Ambient Air Quality Standards in this region³⁵⁻³⁷ (Fig. S2). Area C, which includes the Bay Area and several northern and central inland basins, also facing serious air quality concerns, has a control period from May through October. Great Basin Valley (Area B) is controlled from May through September, and coastal regions (Areas D and E) enter the control period at the latest, beginning in June and ending in September or October.

During the controlled periods, the observed RVP values of summer-blend gasoline remain close to the regulated limit, with an average of 6.98 psi across surveyed stations. After the control period ends, RVP increases gradually as gasoline stations begin selling winter-blend gasoline, reaching approximately 13 psi in December and January. The maximum observed RVP in the CARB survey data is 13.35 psi. Across all regions, RVP changes gradually before and after the control periods, owing to delays associated with fuel production, transportation, and distribution throughout the supply chain²⁹.

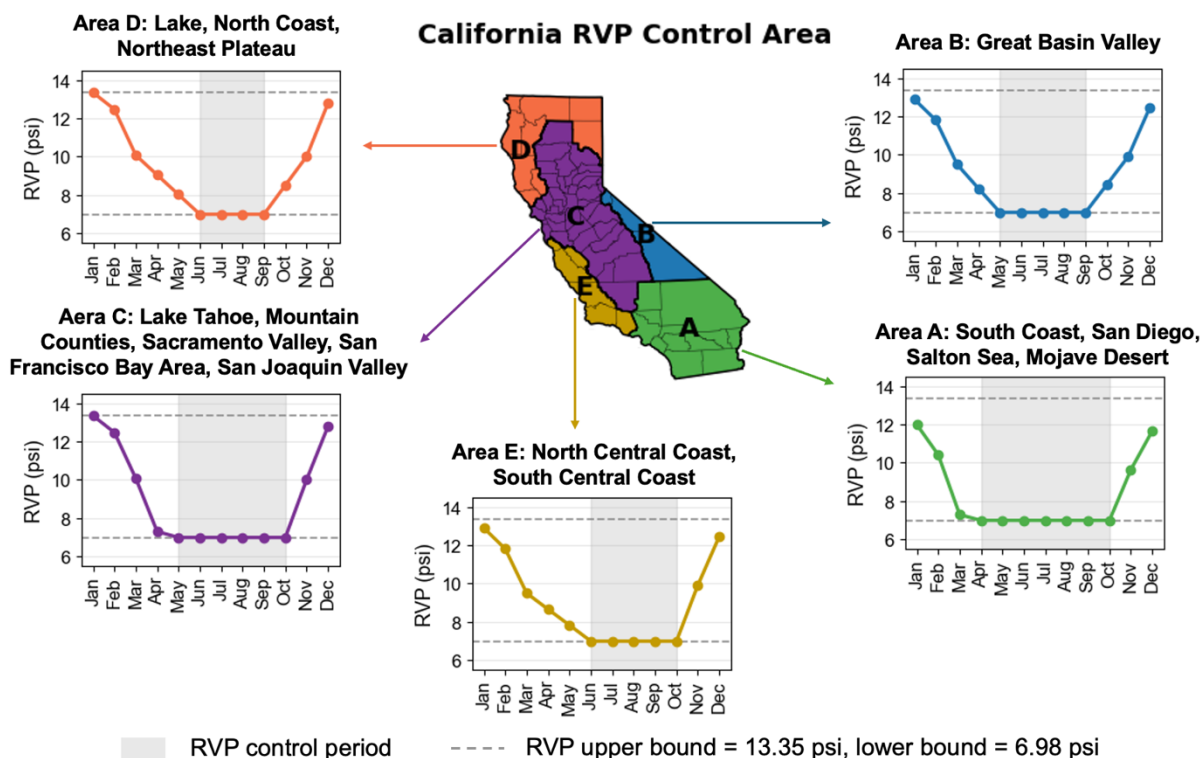


Fig. 1 | Monthly gasoline RVP across California control areas. Panel titles list the air basins included in each control area defined by CARB. The map shows the corresponding RVP control areas; the thinner black boundaries delineate CARB's Geographical Area Index, defined by the intersections of counties and air basins. Monthly average gasoline RVP values are from CARB's gasoline station survey data. Grey shading indicates the summer RVP control period. The dashed horizontal line marks the 13.35 psi upper-bound for RVP in the winter-blend scenarios and the 6.98 psi lower-bound for RVP during controlled periods.

Relaxing volatility control is calculated to increase statewide reactive organic gas emissions by only 1-3% during summer

Figure 2 shows the contributions of different sources to anthropogenic ROG emissions in California for both the Baseline and Winter-blend scenarios. The Baseline scenario used the RVP survey results shown in Figure 1. The Winter-blend scenario applied the upper-bound RVP value of 13.35 psi (the maximum RVP of gasoline based on the CARB survey) for all control areas.

Although on-road and off-road mobile sources contribute to anthropogenic ROG emissions via both evaporative and exhaust emissions, RVP primarily impacts evaporative emissions^{33,38–40}. Therefore, the increases in ROG emissions due to relaxing volatility control is primarily driven by gasoline-related evaporative emissions.

Higher gasoline volatility in the Winter-blend scenario results in slight increases in ROG emissions relative to the Baseline scenario, with larger increases in July than in October (Fig. 2). Under the baseline scenario, gasoline evaporative emissions account for 11.4% and 9.8% of statewide anthropogenic ROG emissions in July and October, respectively. Under the Winter-blend scenario, the contribution of gasoline evaporative emissions increases by 2.7% and 1.1%, reaching 14.1% in July and 10.9% in October, respectively. The larger ROG emission increase in July than October reflects both the higher baseline evaporative emissions at warmer temperatures and the greater difference in gasoline volatility between the Baseline and Winter-blend scenarios. However, the increase remains a small fraction of total statewide anthropogenic ROG emissions and an even smaller fraction of total ROG emissions when biogenic sources are included.

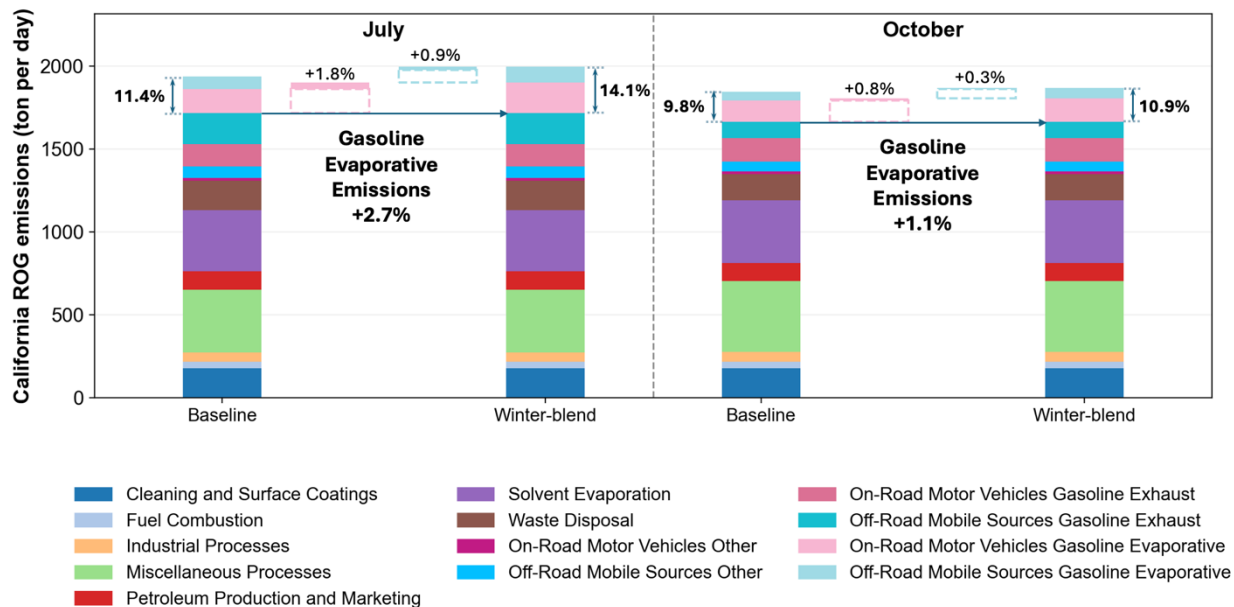


Fig. 2 | Effect of seasonal gasoline volatility standards on statewide anthropogenic ROG emissions. Stacked bars show statewide anthropogenic reactive organic gas (ROG) emissions in 2019 by source category under the Baseline and Winter-blend scenarios for July and October. Percentages denote the contributions of gasoline evaporative emissions from on-road and off-road mobile sources to statewide anthropogenic ROG emissions. Replacing baseline gasoline with winter-blend gasoline increases total anthropogenic evaporative ROG emissions by 2.7% in July and 1.1% in October.

Ozone penalties are largest in July with a maximum increase of 0.4% and 0.35 ppb

Adopting winter-blend fuel affects air quality by increasing evaporative ROG emissions and altering their chemical composition. To disentangle these effects, we compare two winter-blend scenarios against Baseline (Table 1): the Winter-blend scenario, which incorporates both increased evaporative emissions and altered ROG speciation, and the Winter-blend (w/ Baseline speciation) scenario, a sensitivity scenario that isolates the effect of increased evaporative emissions while retaining baseline ROG speciation.

Table 1 | Description of Scenarios

Scenario Name	Scenario Type	Volatility	Chemical Speciation	Description
Baseline	Primary	Real-world RVP values (Fig. 1)	Depending on control area and month	Default scenario following the RVP schedule in Fig. 1
Winter-blend	Primary	Upper bound RVP of 13.35 psi	Winter-blend*	Scenario used to simulate the impact of winter-blend gasoline
Winter-blend (w/ Baseline speciation)	Sensitivity	Upper bound RVP of 13.35 psi	Same as Baseline	Hypothetical scenario used to separate the impact of increasing gasoline volatility alone

*: Winter-blend gasoline-related speciation profiles are used when available. See Methods, Emission inventory development section.

The Winter-blend scenario increases Maximum Daily 8-hour Average (MDA8) ozone in both July and October relative to Baseline, with larger responses in July (Fig. 3b, e). Statewide population-weighted MDA8 ozone increased by 0.075 ppb (0.14%) in July and 0.006 ppb (0.01%) in October (Table 2). The largest increases in monthly mean MDA8 ozone concentrations occur in the South Coast Air Basin (Fig. 3b, e, Fig. S4), reaching a maximum of 0.35 ppb (0.4%) in July and 0.04 ppb (0.04%) in October. This spatial pattern is consistent with the additional ROG emissions from on-road and off-road mobile sources in this area, as well as the ROG-sensitive photochemistry characteristics of urban areas^{1,41}. Overall, the ozone response is small compared to baseline population-weighted average MDA8 ozone concentrations, which are 53.8 ± 5.5 ppb in July and 54.3 ± 4.4 ppb in October. However, they could increase the number of days exceeding the U.S. National Ambient Air Quality Standard (70 ppb) by one to two days in parts of the South Coast Air Basin and the Central Valley in July, or one day for some areas in October (Fig. S5). To put these numbers into perspective, the South Coast Air

Basin experienced over 110 days exceeding the 70 ppb ozone standards per year for all the years from 1980 to 2020⁴². The July increase may be relevant for ozone attainment in the South Coast Air Basin, whereas the October increase is very minimal.

In contrast to ozone, PM_{2.5} concentrations are estimated to decrease slightly under the Winter-blend scenario (Fig. 4b, e). Population-weighted PM_{2.5} would be reduced by 0.001 $\mu\text{g m}^{-3}$ (0.02%) in July and 0.003 $\mu\text{g m}^{-3}$ (0.04%) in October, indicating a negligible response. The largest reductions occur in the South Coast Air Basin, particularly in Los Angeles County, with reductions of 0.004 $\mu\text{g m}^{-3}$ in July and 0.013 $\mu\text{g m}^{-3}$ in October.

Concentrations of air toxics exhibit only minor changes, including a slight decrease in benzene concentrations in both months due to changes in gasoline chemical composition. Other air toxics changes are very limited, with different impacts in July and October (Table 2).

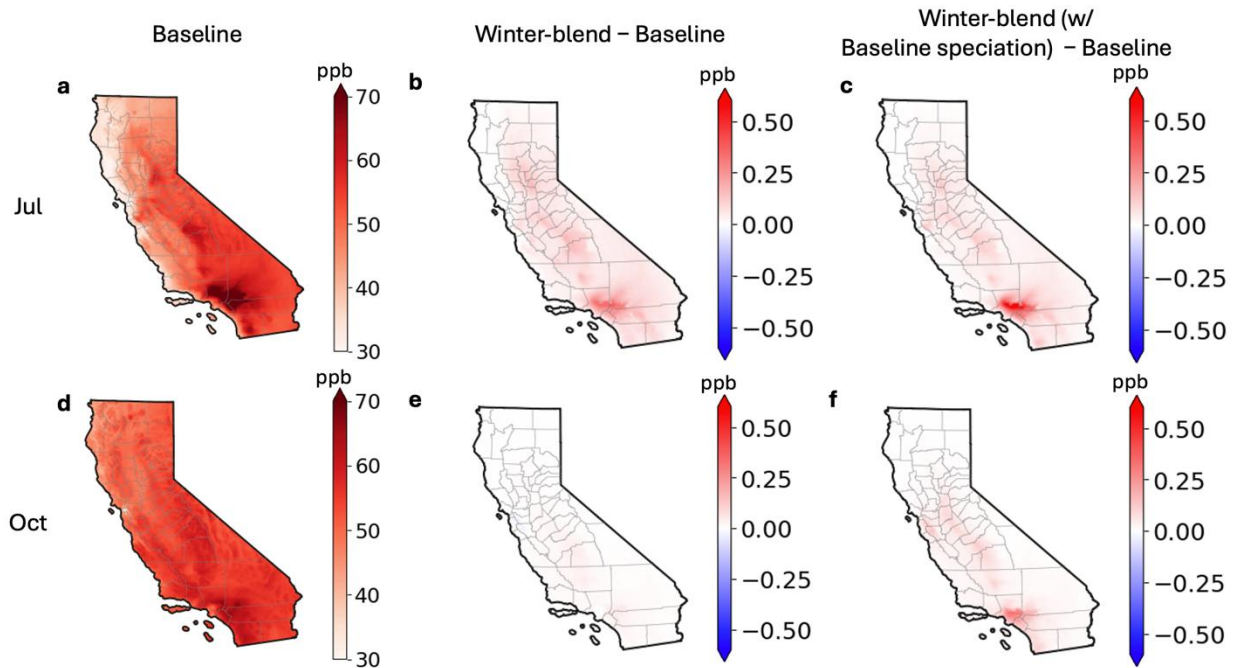


Fig. 3 | Spatial patterns of monthly averaged MDA8 ozone concentrations in California. a, d Baseline concentrations. **b, e** Changes in concentrations between Winter-blend scenario and Baseline in July and October. **c, f** Changes in concentrations between Winter-blend (w/ Baseline speciation) scenario and Baseline in July and October. The grey lines represent the county boundaries.

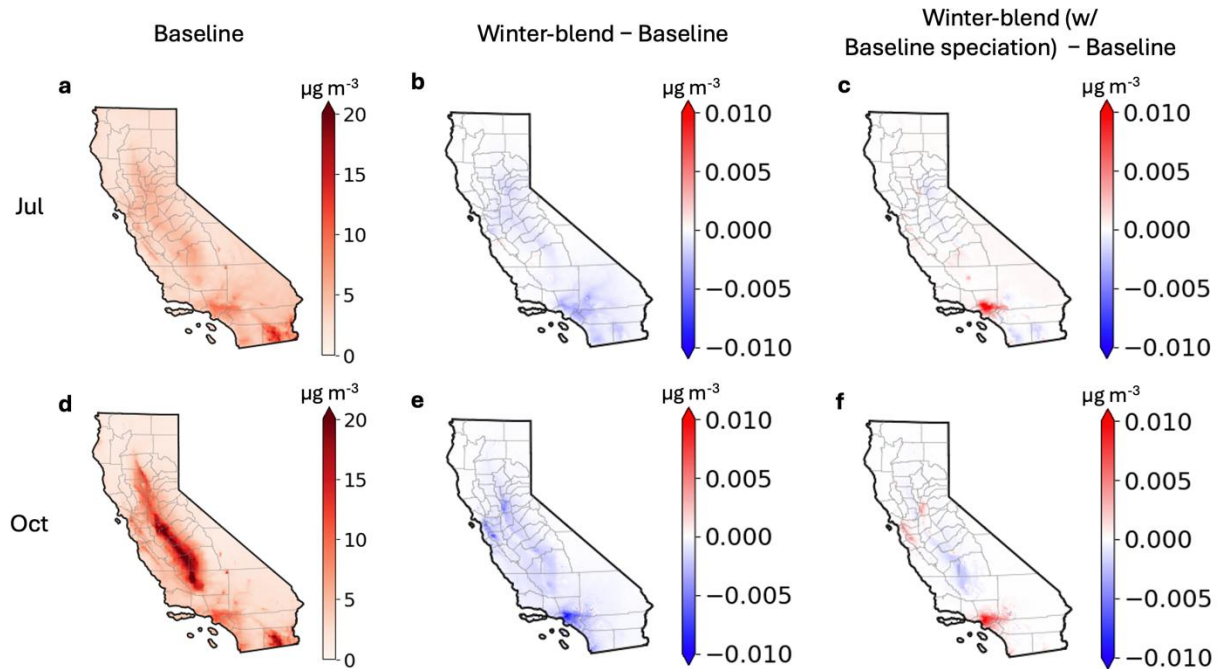


Fig. 4 | Spatial patterns of monthly averaged daily PM_{2.5} concentrations in California. a, d Baseline concentrations. **b, e** Changes in concentrations between Winter-blend scenario and Baseline in July and October. **c, f** Change in concentrations between Winter-blend (w/ Baseline speciation) scenario and Baseline in July and October. The grey lines represent the county boundaries.

Table 2 | Population-weighted average concentrations of air pollutants under the Baseline scenario and absolute and percentage changes relative to Baseline of winter-blend scenarios

Air pollutant concentrations	Baseline		Winter-blend – Baseline		Winter-blend (w/ baseline speciation) – Baseline	
	July	Oct	July	Oct	July	Oct
MDA8 ozone (ppb)	53.80	54.34	0.075 (0.14%)	0.006 (0.01%)	0.14 (0.26%)	0.068 (0.12%)
PM _{2.5} (µg m ⁻³)	5.954	8.182	-0.001 (-0.02%)	-0.003 (-0.04%)	0.003 (0.06%)	0.003 (0.03%)
Benzene (ppb)	0.087	0.129	-0.001 (-1.28%)	-0.003 (-2.39%)	0.002 (2.58%)	0.002 (1.34%)
Formaldehyde	1.620	1.611	0.005	0.003	0.007	0.004

(ppb)			(0.33%)	(0.20%)	(0.41%)	(0.24%)
Acetaldehyde	0.499	0.666	0.009	0.006	0.011	0.007
(ppb)			(1.72%)	(0.89%)	(2.23%)	(0.99%)
Toluene	0.218	0.338	0.0003	-0.003	0.006	0.005
(ppb)			(0.13%)	(-0.94%)	(2.69%)	(1.41%)
Xylene	0.095	0.154	0.0002	-0.0007	0.002	0.002
(ppb)			(0.22%)	(-0.46%)	(2.12%)	(1.15%)

204

205 **Both higher volatility and fuel composition contribute to the change in air quality**

206 To isolate the effect of higher evaporative emissions from the effect of fuel composition, we
207 compare the Winter-blend scenario with the Winter-blend (w/ Baseline speciation) scenario. The
208 Winter-blend (w/ Baseline speciation) scenario would produce larger ozone increases, with
209 statewide population-weighted MDA8 ozone increased by 0.14 ppb in July and 0.068 ppb in
210 October, compared with 0.075 ppb and 0.006 ppb under the Winter-blend scenario. The
211 maximum grid-cell increase would reach 0.62 ppb (0.8%) in July in the South Coast Air Basin
212 (Fig. 3c, f). The responses of PM_{2.5} to winter-blend fuel switch when assuming fixed chemical
213 speciation profiles would be more heterogeneous, with small increases in parts of the South
214 Coast Air Basin and Bay Area and small decreases in parts of the Central Valley (Fig. 4c, f).
215 Population-weighted increases would be 0.003 $\mu\text{g m}^{-3}$ (0.06%) in July and 0.003 $\mu\text{g m}^{-3}$ (0.03%)
216 in October. This heterogeneous response reflects spatial variation in precursor composition and
217 oxidant availability, which affects secondary organic aerosol formation⁴³.

218 Comparing the two Winter-blend scenarios indicates that changes in ROG composition
219 partially offset or overturn the air quality impacts of increased evaporative ROG emissions. The
220 Winter-blend scenario produces lower PM_{2.5} and benzene concentrations than the Winter-blend
221 (w/ Baseline speciation) scenario, consistent with lower fractions of benzene and other secondary
222 organic aerosol (SOA) precursors in the chemical speciation profiles of winter-blend emissions
223 (Table S1, Fig. S6). As a result, despite higher total evaporative ROG emissions, ambient
224 concentrations of benzene and PM_{2.5} decrease slightly when winter-blend speciation is
225 considered, especially in densely populated areas (Fig. S7; Fig. 4b, e). In contrast, formaldehyde
226 and acetaldehyde show similar increases across the two scenarios, reflecting their comparable
227 fractions in the chemical speciation profiles of summer and winter-blend gasoline. For aromatic
228 species such as toluene and xylene, the Winter-blend scenario yields smaller increases in July
229 and larger decreases in October than the Winter-blend (w/ Baseline speciation) scenario,
230 reflecting the combined influence of increased evaporative emissions and reduced aromatic
231 content in the winter-blend fuel composition (Fig. S6).

233 Cost savings outweigh monetized health effects

234 As shown in Fig. 5, the monetized health impacts of adopting winter-blend gasoline are small
235 relative to the potential estimated fuel cost savings. Under the Winter-blend scenario, increased
236 ozone concentrations produce a negative monthly health impact of \$13.9 million in July and \$1.5
237 million in October. Monetized health impacts include mortality and morbidity such as hospital
238 admissions (see Methods, Table S7), and the detailed output for each health endpoint is shown in
239 Table S8. However, these damages are partially offset or reversed by PM_{2.5}-related health
240 benefits of \$2.9 million in July and \$6.7 million in October. Under the Winter-blend (w/ Baseline
241 speciation) scenario, which can be considered as the hypothetical worst-case scenario, both
242 ozone and PM_{2.5} contribute to adverse health impacts in July and October.

243 Summer-blend gasoline is more costly to produce than winter-blend gasoline because low-
244 RVP requirements limit the use of higher-volatility and lower-cost blending components, such as
245 butane²⁹. Under conservative assumptions (see Methods), we estimate that relaxing seasonal
246 RVP standards would reduce production costs by approximately 6.1 cents per gallon in July and
247 5.9 cents per gallon in October, corresponding to statewide savings of \$73.4 million and \$70.4
248 million, respectively; these savings are approximately 6.7 times and 13.5 times the estimated
249 health impacts from air quality changes. Applying a higher cost estimate reported in the literature
250 increases the estimated savings to \$154.1 million in July and \$147.9 million in October (see
251 Methods). Even the higher cost saving estimates may understate the broader economic impact
252 because (1) we used the lower-bound impact based on earlier studies of federal conventional
253 gasoline standards⁴⁴, (2) the compliance costs associated with California's fuel specifications
254 may be higher, and (3) the change may induce additional supply-chain savings beyond lower
255 production costs. For example, winter-blend gasoline could increase access to importable fuels
256 during refinery maintenance or periods of supply tightness, resulting in additional savings.

257 California's early winter-blend authorizations in 2022 and 2023 provide supporting real-
258 world evidence for reducing gasoline price^{13,28}. As shown in Table S2, California's retail gasoline
259 price relative to the U.S. average declined by \$0.51-0.86 per gallon within four weeks after the
260 authorizations, whereas comparable periods in other years showed much smaller changes. This
261 price difference corresponds to roughly \$500-900 million per month of statewide consumer fuel
262 expenditure. While these observations do not establish a causal relationship, they are consistent
263 with the hypothesis that earlier access to winter-blend gasoline may alleviate supply constraints
264 and mitigate gasoline price spikes^{7,45,46}.

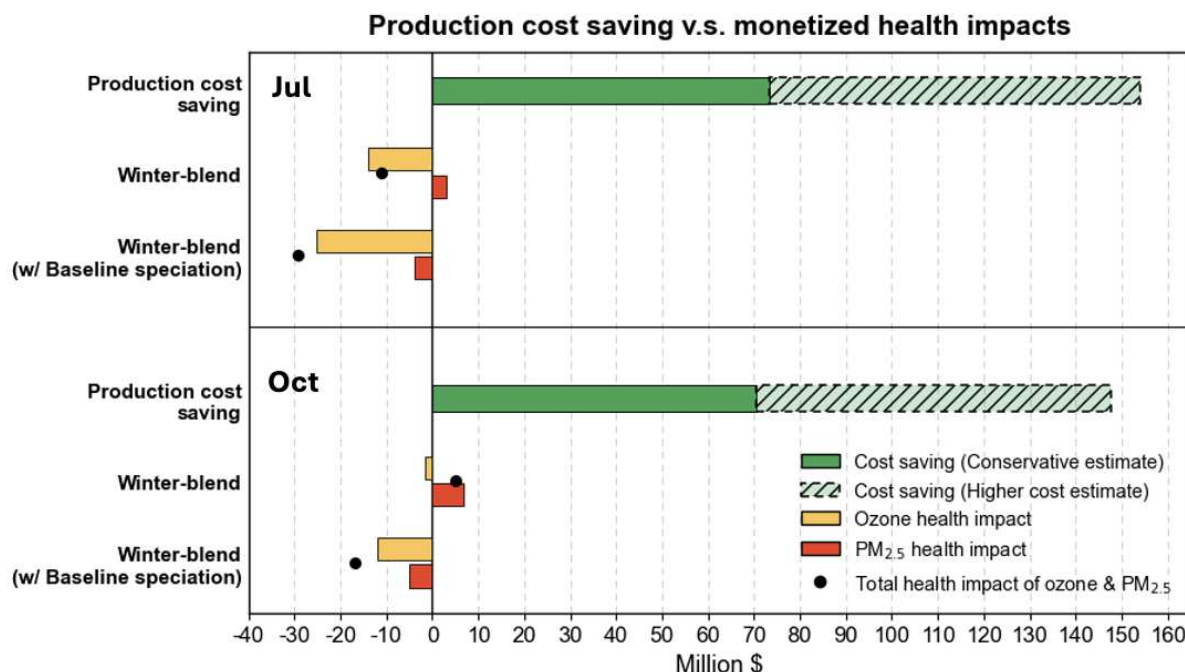


Fig. 5 | Comparison of monthly refinery production cost savings and monetized health impacts associated with relaxing seasonal gasoline volatility standards. Solid and hatched green bars denote conservative and a higher cost estimate of cost savings, respectively. Orange and red bars represent monetized health impacts of ozone and PM_{2.5} respectively, and black circles indicate the combined monetized health impact.

Discussion

Relaxing California's current summer-blend gasoline requirements is calculated to produce only moderate to negligible air quality impacts. Since the additional evaporative ROG emissions in the winter-blend scenarios represent a very small fraction of statewide anthropogenic ROG emissions (Fig. 2), we estimate ozone increases to be small and PM_{2.5} responses to be negligible. The worst air quality impact is predicted under the Winter-blend (with Baseline speciation) scenario in July, resulting in a maximum ozone increase of 0.62 ppb (0.8%) and a population-weighted ozone increase of 0.14 ppb (0.26%) relative to the Baseline scenario. The October response is smaller, with a maximum ozone increase of 0.20 ppb (0.33%), and a population-weighted average increase of 0.068 ppb (0.12%). PM_{2.5} response remains very small across both months and scenarios, with population-weighted average change at around ± 0.001 - $0.003 \mu\text{g m}^{-3}$ ($\sim 0.05\%$).

A key finding is that the air quality impact of winter-blend adoption cannot be evaluated based on fuel volatility alone. Although higher volatility increases evaporative ROG emissions, changes in winter fuel composition partly offset or reverse the resulting air quality penalty. Compared with the Winter-blend (w/ Baseline speciation) scenario, using an improved ROG

chemical speciation profile reduces ozone increases and even produces slight decreases in PM_{2.5}, consistent with lower fractions of SOA precursors in winter-blend gasoline^{33,47} (Table S1). Thus, considering the increase in total organic gas emissions alone would overestimate the air quality penalties of winter-blend adoption. Improved characterization of chemical speciation profiles across fuel formulations for gasoline-related emissions would further reduce uncertainties in these estimates. Regulatory discussions often treat winter-blend gasoline as a more volatile fuel that generates higher emissions; however, the air quality response also depends on the chemical composition of the ROG species emitted.

The analysis was further extended to quantify the monetized health impacts and associated economic costs. Winter-blend gasoline would result in net health damages in July but a slight net health benefit in October because of reduced PM_{2.5} concentrations. Across all cases, estimated fuel cost savings far exceed the simulated health impacts, suggesting net savings of relaxing gasoline volatility limits for both months (Fig. 5). These results suggest that October is a more favorable period for relaxing seasonal RVP standards than the peak summer months and is a low-risk option. Our scenarios apply an upper-bound RVP of 13.35 psi statewide for an entire month to estimate the upper-bound air quality impacts. In practice, advancing the transition from summer-blend to winter-blend gasoline by one month would increase October RVP by approximately 1.5-3.0 psi (Fig. 1) as the fuel distribution system turns over. The associated production-cost savings and air quality impact would also accrue across the expanded winter-blend supply period rather than only within October, indicating actual air quality impact would be even smaller than our already small estimates.

Although our analysis captures the primary effects of relaxing seasonal RVP standards, several additional factors could influence the magnitude of the estimated impacts. First, we assume that vehicle miles traveled (VMT) is fixed across scenarios, whereas cheaper fuel can induce more VMT⁴⁸. Second, we use 2019 meteorology that does not capture future climate warming, which raises both evaporative emissions and the rate of photochemical ozone formation, to isolate the impact of emissions. With California ozone projected to rise by roughly 1-5 ppb by mid-century²⁰, the modest penalty we identify could grow under future conditions. However, natural turnover of older and higher-emitting vehicles would reduce the impacts of fuel blend on ROG emission increases.

The policy relevance of these findings is increasing as California's in-state gasoline supply becomes more constrained. California is projected to lose approximately 17% of its in-state refining capacity during 2025–2026 following the closures of the Phillips 66 Los Angeles refinery and the Valero Benicia refinery²⁷. While a number of out of state refineries do produce California-grade gasoline and blending components (which has allowed the California market to balance through imports), improving fuel supply flexibility would still make the state less vulnerable to disruptions and therefore provide increasing economic value under a tightening supply outlook. Furthermore, ongoing policy discussions on fuel-market resilience and the transportation fuels transition, including SB 237⁴⁹ and the Transportation Fuels Transition Plan⁵⁰,

suggest that California could also consider adopting readily available federal fuel formulations to increase gasoline fungibility. Aligning both volatility limits and fuel speciation with national standards could lower costs and expand competitive supply options for California gasoline.

Potentially more cost-effective strategies may be available for achieving comparable ROG emission reductions than adopting California's current strict summer-blend fuel requirements. For example, the additional ROG emissions estimated under the Winter-blend scenario were 51 tons per day in July and 13 tons per day in October, comparable in magnitude to emissions from selected small off-road gasoline equipment categories in California⁵¹ (Table S9). California policies, including AB-1346, CARB regulations, and South Coast Air Quality Management District incentives, have started promoting the electrification of lawn and garden equipment to reduce near-source exposure and noise^{52–54}. Another strategy is to incentivize the retirement of old vehicles, as the July ROG emission increases are equivalent to approximately 24% of total ROG emissions from pre-2004 gasoline vehicles⁵⁵ (Table S9). These comparisons, together with long-term declines in statewide emissions and ambient concentrations of anthropogenic ROG across several regulated source categories^{56,57}, suggest that California could further consider a more flexible approach to controlling gasoline-related ROG emissions. One policy option would be to allow greater fuel volatility flexibility while applying a 5–6 cent per gallon tax to higher-volatility gasoline, which reflects the associated production cost savings. Its revenue could support other cost-effective measures to offset the additional ROG emissions. Such a policy would require location- and season-specific evaluation, however, because equal ROG reductions from different sources may not provide the same air quality benefits as their emissions differ in location, timing, and chemical composition.

A comprehensive assessment would need to account for refinery constraints, uncertainty in RVP-related production costs, gasoline price responses, fuel import availability, and spatially resolved health impacts. Future work could extend the analysis across additional years and months, further characterize uncertainty in fuel composition and market responses, and evaluate the implications of relaxing federal seasonal volatility standards at the national scale. As California seeks to balance air quality objectives with economic considerations, integrated evaluations of both environmental and economic outcomes will be increasingly important for identifying the most cost-effective policy strategies.

358 Scenario development

359 As shown in Table 1, we develop scenarios to evaluate the potential air quality consequences of
360 relaxing California's seasonal gasoline volatility requirements. The Baseline simulation used the
361 default California gasoline RVP schedule and default ROG speciation profiles for summer-blend
362 gasoline. The Winter-blend scenario represents the combined effects of higher gasoline volatility
363 and changes in fuel composition. Specifically, gasoline RVP is increased to 13.35 psi, the
364 maximum value observed across California gasoline control areas and months in 2019; available
365 winter-blend ROG speciation profiles for gasoline-related exhaust and evaporative emissions are
366 applied from the CARB speciation profile database⁵⁸. Note that season-specific chemical profiles
367 are not available for all gasoline-related emission sources; therefore, winter-blend speciation
368 profiles were applied in the Winter-blend scenario only to sources for which such data are
369 available. Furthermore, we construct a sensitivity scenario, referred to as Winter-blend (w/
370 Baseline speciation) to isolate the effect of increased total ROG evaporative emissions while
371 holding the chemical composition of ROG constant. In this scenario, gasoline RVP is set to
372 13.35 psi, while the ROG speciation profiles are kept identical to the Baseline profiles.

373 Emission inventory development

374 For on-road mobile sources, we use the latest version of the Emission FACtors (EMFAC) model,
375 EMFAC2025 (version 2.0.0)³⁴, to quantify emissions across different scenarios. EMFAC
376 estimates emissions of air pollutants, including PM, NO_x, and total organic gases (TOG), which
377 includes methane and ROG. Adopting winter-blend fuel would increase the fuel RVP and TOG
378 evaporative emissions, but not TOG exhaust emissions, which are mainly dependent on vehicle
379 aftertreatment technology and other fuel properties according to EMFAC. When calculating
380 evaporative emissions, we use EMFAC default RVP input for the Baseline scenario based on
381 CARB survey data. For winter-blend scenarios, we input the upper-bound RVP value of 13.35
382 psi to EMFAC to generate on-road emission inventories. We then use the Emissions Spatial and
383 Temporal Allocator (ESTA) model to disaggregate total emissions into a spatially and
384 temporally resolved emission inventory for air quality modeling.

385 For off-road mobile sources, Baseline emission inventories are obtained from CARB and
386 processed using Sparse Matrix Operator Kernel Emissions (SMOKE). For winter-blend
387 scenarios, we multiplied baseline gasoline-related off-road evaporative TOG emissions with
388 month-specific scaling factors derived from the ratio of winter-blend to baseline TOG emissions
389 from gasoline-related on-road evaporative sources (1.27 in July and 1.12 in October).

390 Chemical speciation profiles of gasoline evaporative and exhaust TOG emissions are
391 different between summer-blend and winter-blend gasoline, but paired profiles are not available
392 for some source categories in CARB's speciation database⁵⁸. We used summer-blend gasoline
393 speciation profiles for Baseline and Winter-blend (w/ Baseline speciation) scenarios, and winter-

blend gasoline speciation profiles for Winter-blend scenario when available. Specifically, paired summer-blend and winter-blend profiles are available for on-road exhaust emissions and some off-road evaporative sources (Table S1).

Emission inventories for all other anthropogenic sectors are also obtained from CARB, processed using SMOKE, and held constant across the three scenarios. Biogenic emissions are calculated online using the Biogenic Emission Inventory System (BEIS) module in the Community Multiscale Air Quality (CMAQ) model.

Air quality modeling and monetized health impact valuation

We conduct air quality simulations using CMAQ v5.5, driven by meteorological fields from the Weather Research and Forecasting model (WRF) v4.6.1. The 4-km modeling domain covered the entire state of California, consistent with previous studies published by our group⁵⁹. We select July and October to capture the hottest summer meteorology and a cooler period near the end of the control season in 2019, respectively (Fig. S3). Gas-phase chemistry was represented using the SAPRC07 mechanism with the AERO6 aerosol module. Boundary conditions are derived from the Community Atmosphere Model with Chemistry (CAM-chem) outputs⁶⁰. Detailed model configurations are shown in Table S4. Our CMAQ model performance for the Baseline simulation is within benchmark compared to EPA Air Quality System monitoring data and is summarized in Table S5.

Because all scenarios share an identical modeling framework and differ only in gasoline evaporative emissions and TOG speciation, the reported concentration changes are based on paired scenario differences rather than absolute predictions. While uncertainties in absolute concentrations remain, systematic errors common to all simulations are expected to largely cancel, allowing the model to more robustly quantify the incremental impacts of winter-blend gasoline. Population-weighted exposure metrics are calculated by intersecting CMAQ grid cells with census tract boundaries and weighted by population data from the 2019 American Community Survey⁶¹.

Monetized health impacts are estimated using the EPA Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) following the methodology of previous health impact assessments in California^{62,63}. Population data for the base year 2019 are used for this study. The concentration-response functions for both pollutants are selected from the best available mortality and morbidity functions in the EPA standard functions within BenMAP (Table S7). Note that because BenMAP does not support ozone health impact calculations outside its ozone season, we assign October ozone concentrations to the corresponding July calendar dates to estimate the associated health impacts, which should be considered as upper-bound estimates for health impacts in October.

The estimated mortality changes are multiplied by the value of a statistical life (VSL). The estimated morbidity changes are multiplied by the unit cost of each visit. VSL and the unit cost of hospital admission and emergency department visits are selected from the EPA standard

valuation function (2023) and are shown in Table S7 in 2015 dollars. All calculated monetized health impacts are adjusted to 2019 dollars in Table S8 using the Consumer Price Index (CPI) inflation data⁶⁴.

Estimation of production cost savings

Total production cost savings are estimated by multiplying the per-gallon production cost savings from relaxing RVP requirements by California's total gasoline consumption. Previous studies suggest that reducing gasoline RVP increases production costs by 0.5 cents per gallon per psi in a 1999 study⁴⁴ to 2.1 cents per gallon per psi in a 2021 study⁶⁵. Using the Consumer Price Index, we convert these estimates to 0.96–2.016 US cents per gallon per psi in 2019 dollars.

The potential production cost saving per gallon is calculated as the difference between the upper-bound winter-blend RVP value of 13.35 psi and the observed statewide average RVP from CARB survey data, multiplied by the inflation-adjusted cost estimates. The observed statewide average RVP is 6.98 psi in July and 7.24 psi in October, corresponding to potential cost savings of 6.1 cents per gallon and 5.9 cents per gallon, respectively. The average of California gasoline consumption for year 2019 is 38.7 million gallons per day in both July and in October⁶⁶. The final production cost savings are calculated by the cost savings per gallon and the amount of gasoline consumption in California (Table S6).

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Data availability

CMAQ source code is available at: <https://github.com/USEPA/cmaq>. Data for chemical speciation profiles are from CARB database: <https://ww2.arb.ca.gov/consolidated-list-speciation-profiles> (ref 58). Initial and boundary condition data used for CMAQ are available at CAM-Chem website: <https://www.acom.ucar.edu/cam-chem/cam-chem.shtml> (ref 60). Census-tract level population data can be accessed from the 2019 American Community Survey: <https://dof.ca.gov/reports/demographic-reports/american-community-survey/#ACS2019x1> (ref 61). Model output data used for analysis are available via Zenodo at: <https://doi.org/10.5281/zenodo.21522853>.

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468 Code availability

469 Code used for analysis is available via Zenodo at: <https://zenodo.org/records/21522853>.

470

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654 **Contributions**

655 J.Z., S.H. and P.O.W. conceived the study. X.Z. and J.Z. developed the methodology. X.Z., H.H.
656 and M.B. curated the data and conducted the analyses. X.Z. performed the emissions and air
657 quality simulations. X.Z., H.H., M.B., Y.A., E.P., S.H. and P.O.W. interpreted the findings. X.Z.
658 wrote the initial draft. H.H., M.B., Y.A., E.P., S.H. and P.O.W. reviewed and edited the
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664 **Ethics declarations**

665 Competing interests

666 The authors declare no competing interests.

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